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A review on electrical machines insulation aging and its relation to the power electronics arrangements with emphasis on wind turbine generators

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ABSTRACT

This paper is a review of work performed on a subject that is relatively novel, that of wind generators in conjunction with power electronics arrangements. It is known that power electronics arrangements may give rise to unwanted spikes that may stress unnecessarily high the insulating systems of motors and generators. The influence of various waveforms of different rise times on the insulating system's lifetime is investigated as well as the influence on the PD activity. The present paper offers also some proposals for future research.

Contents

1. Introduction

Current EU targets are to deliver 35% of electricity from wind power by 2020. Although at present current EU figures are much less than that, efforts are being made all over Europe (and indeed the world) to increase the dependence on renewable energy sources [1]. Such challenges, which will shape the future of electricity demand, require good insulating systems, which in turn can function without problems for long periods. In other words, insulating system aging is one of the primary concerns of the researchers worldwide. Operation and maintenance of wind turbine generators – and indeed of offshore wind farms – is much more difficult and expensive than for their onshore counterparts. In [2], it was pointed out that the current reliability and failure modes of commercial offshore wind turbines are such that a "no maintenance" strategy is not a viable option. Consequently, improved preventive and corrective maintenance schemes will become crucial for the economic exploitation of offshore wind power.

There are a number of papers concerned with the basic principles and electrical conversion systems in wind turbine generators (Fig. 1), where problems regarding the insulating systems involved are mentioned [3]. Voltage variations may cause particular stressing on the insulating systems, and therefore, depending on the time period of such variations, the wind turbine has to be disconnected. Another aspect of the problematic is the occurrence of independent faults in a few minutes intervals, which may also provoke the turbine disconnection [4]. Power electronics arrangements, especially those related to high switching speeds, may require special filters and limited voltage gradients in order to prevent excessive stressing of the generator insulation as in Fig. 2.

There is a vast body of technical literature concerned with generator insulation aging [6,7]. A major cause – but not the only one – is the partial discharges (PD) which may develop and deteriorate the generator insulation [8,9]. Furthermore, attention has been paid by numerous researchers to the fact that the generator insulation is subjected to multi-factor stresses and consequently, such a combination of stresses (electrical, thermal, mechanical, etc.) shortens considerably the lifetime of the insulation [10]. In a comprehen-

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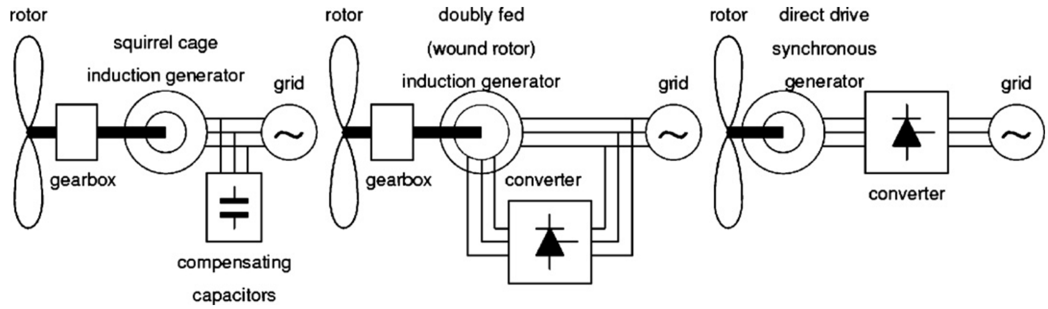


Fig. 1. The three commonly used generator systems [3].

sive review, Thomson [11] points out that electrical failures are due to a combination of several factors. Salinity, for example, in offshore arrangements may play a role and it may act synergetically with other aging factors. Vibration that may come from electromagnetic forces or from mechanical problems, is another major cause of premature degradation of a winding.

With the new technologies and the advent of wind turbine generators, such subjects became of great interest from the part of the researchers as well as from the part of industry [1]. One of the aspects which has to be further studied is the relation of wind turbine generator aging with the phenomena that might be caused by power electronics arrangements, such as inverters, which in turn might cause sudden voltage rises and frequency changes. Voltage and frequency changes may cause PD phenomena that might provoke premature aging [6–10].

The authors of the present paper aim to give a review of the work performed on the influence power electronics arrangements have on the aging and lifetime of wind turbine generator insulation systems. Particular emphasis is given to the PD, which may affect the lifetime of such insulation.

2. Aging of wind turbine generators and partial discharges

Aging consists a major challenge regarding all sorts of insulating systems, and consequently also those of wind turbine generators. Aging may come from a variety of causes, be them electrical, thermal, mechanical or others. Models developed for the aging study of generators include those of Ramu [12], Simoni [13], Fallou et al. [14], Crine et al. [15,16], where the mathematical complexity goes in hand with the difficulty of the combined stresses on such insulating systems. An excellent review of the aforementioned models can be found in Gjaerde [17], where the strong as well as the weak aspects of such models are mentioned. The general approach of the above models [12–17] is very similar, with the connotation that these models run into problems when temperature and voltage approach their maximum values. It is then evident that, in such values of temperature and voltage, the minimum time-to-breakdown cannot be predicted with great accuracy. Crine's model gives another look to the question of aging, by underlining the importance of thermodynamics, the thermally activated processes and the activation barriers. Whereas the first three models consider time-to-breakdown as inversely proportional to the aging rate, Crine's model considers time-to-breakdown as equal to the inverse aging rate. Insulating systems in general, and generator insulating systems in particular, are subjected to such interpretations regarding aging. Regarding electrical machines insulation, the aging processes can vary depending on the various types of tests. In general, however, the aging processes (and also the aging behaviour) can be divided in two categories: long-term behaviour and short-term behaviour. The former conforms with the aging at relatively low stresses, whereas the latter conforms with rather higher stresses [18]. In real systems, and in real conditions of functioning, aging consists one of the major challenges to this date. One, however, should not forget that aging is also – or primarily – dependent on the type of materials used [19]. A major factor which is emphasized in the aging process is the temperature, which determines to a great extent the resulting deterioration of an insulating system as well as the chemical processes involved [17]. In [17], it was pointed out that there may be a physical parameter to be linked with the aging process, namely, the gas pressure in an enclosed cavity, the large reduction of which may mean a short time to ultimate insulation failure. In [20], a model proposed for multistress aging in micaceous insulation is based upon the thermal aging (causing decomposition gas and delaminations at the interfaces), the mechanical fatigue (which causes delamination and cracks in epoxy and mica) and voltage endurance (which causes PD in defects, tree development and eventual electrical breakdown and/or mechanical rupture).

On the other hand, partial discharges (PD) which are caused by excessive electrical stresses and/or by defects in insulating systems, consist a very significant threat to the lifetime of generator insulating systems. PD may also be caused by moderate electrical stresses under the influence of temperature cycles, mechanical stresses, etc. [21,22]. In the context of this paper, PD will be considered as one of the major hindrances to the orderly functioning of the wind turbine generator insulation and an effort is being made to try to relate PD phenomena with electrical stresses caused by power electronics arrangements.

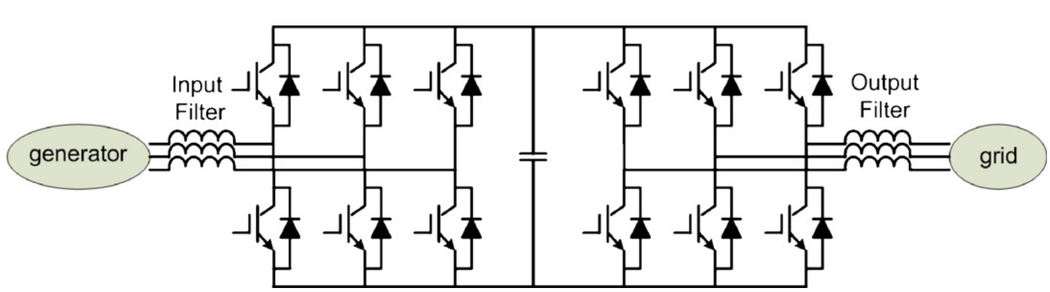


Fig. 2. Structure of the back-to-back Voltage Source Converter [5].

Table 1
Insulating system for low voltage wind turbine generators (690–900 V) [23].

Insulating materials for 690–900 V random wound coils	
Winding wire	Thermex® 200 or SamicaShield® (Samica® insulated round wire)
Slot insulation	Myoflex PVS (impregnated PETP fleece/film/fleece) or Myoflex 2N50/80 (Nomex®/PETP film/Nomex®) or Myosam (PETP film/Samica®/PETP film) or Myoflex 2N80S (Nomex®/Samica®/Nomex®) for the slot portion and Myoflex 2N130S (Nomex®/Samica®/Nomex®) for the end winding
Impregnating resin	Damisol 3040 (UPI resin) or Damisol 3032 (UPI resin)
End winding tape	4616/18 (adhesive glass fabric)
Wedges/closures	Myoflex PVS (impregnated PETP fleece/film/fleece) or Vetronite 64.120 (Glass fabric/epoxy composite material)
Finishing varnish	Damicoat 2404/07 (air drying varnish)

3. Research performed

The insulating materials used for wind turbine generators are basically the same as for conventional generators. However, such materials must be carefully selected in order to satisfy the specific requirements of the wind turbines (e.g. Table 1), which are the frequent exposure to weather conditions, the sudden start and stop of the generator, the compatibility with the power electronics arrangements that accompany the generator [23]. There is work reported on maintenance and repair for wind turbine generators, although such work was mainly orientated to the mechanical parts (e.g. roller bearings and friction bearings) and not to the electrical parts [24].

Power electronics arrangements for the machine speed control, such as Pulse Width Modulation (PWM), may lead to new constraints and limitations. As is reported in [25], high pulse frequencies range and voltage shapes that differ from the usual AC voltage, can change the behaviour of insulating materials used in generator insulation [26,27]. In [25], it is evident that short pulses with fast fall fronts induce surface charges in the insulation that are trapped. Such charge concentrations are not observed with AC voltages, which means that fast pulses influence in a particular way the insulation system. Surface charges are built in the insulating material for electric fields that are lower than the ones necessary for usual bulk charge injection. Although Ref. [25] refers to laboratory experiments, it is evident that such surface charging will influence PD activity. Charge trapping becomes highly interesting when there are polarity reversals. In yet another paper, although the importance of voltage application at variable frequencies was stressed, it was also noted that the degradation of insulation by rated stresses alone, is a slow process, which may be accelerated if the insulation is exposed to thermal overload for several hours and then natural cooling. However, it must be remarked that the variable frequencies were not in the range of kHz [28].

Inverter-fed motors under certain conditions may cause such a voltage magnitude, so that voltage spikes quite large may ensue which will have as a result the uneven electric stress distribution throughout the coils [29]. These overvoltages are the result of overshoot at the drive's output, impedance mismatch between the drive and the motor, and the PWM algorithm used by the drive [30]. Such stressing may cause steady degradation of the insulation in both magnet wires and the main insulation. The rise time of the resulting voltage waveforms have a pronounced effect on the PD inception voltage level of the whole system [30], although research has also indicated that the number of discharges under PMW operation did not seem to depend on the rise time of the applied voltage [29]. A change in rise time from 1 μs to 0.02 μs resulted in a 15% reduction of the PD inception voltage level of tests performed on twisted pairs [30,31]. Such deterioration phenomena due to steep rise voltages, led some manufacturers to develop specific insulating systems to be more "corona resistant" [32–34]. In [35], it was clearly shown that, as far as motor insulation is concerned, fast rise time square voltages of 2 μs gave lower PD inception voltage than square voltages with rise times of 100 μs. A reason for this is because PD in motor insulation is found to occur already at the voltage flank, only microseconds after the voltage change. Moreover, it is the pulse repetition rate that also may cause a worsening in insulation performance, as was noted in [36–37], where the inception voltage with a repetition rate of 60 pps (pulses per second) was lower than the inception voltage with a repetition rate of 6 pps. In experiments performed with cavities in polycarbonate plates, it was shown that PD extinction voltage was lower at the shorter rise time. For the shorter rise time a number of voltage levels were found where the number of PD per period was almost constant, whereas for the longer rise time, the number of PD increased about linearly with the applied voltage level [38]. Voltage waveforms produced by PMW may cause PD patterns quite different from those of normal sine or square voltage waveforms [39]. Voltage waveforms produced by PMW may, furthermore, increase the losses in an insulation system more than double than sinusoidal waveforms [40,41]. In [11], a mentioning of PD at inception level is also made, namely that, insulation failures may occur not only from large magnitude PD but also from machines working at their nominal voltage.

Techniques that can be used for wind generator diagnosis can include the dismantling of the whole turbine and then by testing the windings, their condition may be determined. Besides that, given that solid byproducts may result as a consequence of PD activity and/or vibration, Scanning Microscopy (SEM) and Energy Dispersive Analysis (EDX) may help in defining better the chemical constituents [42]. Work performed several years ago on rotating machine insulation, suggested that a variety of diagnostic measurements are needed for a better estimate of the state of degradation, such as incremental loss tangent and capacitance change, besides PD measurements. A more thorough approach to the problem of wind generator diagnosis would include also a statistical analysis of several PD parameters and their correlation to the loss tangent and the capacitance change [43].

Inverter surge voltages may cause PD with an increase in the operating voltage in inverter-fed motors. PD become thus important not only for the machine itself but also for the insulation of the wires that are exposed to repetitive surge voltages with short rise times of several tens or hundreds of nanoseconds [44]. It becomes evident that the system of generator insulation and of the connecting wires has to be examined as a whole. In this respect, nanocomposite materials, especially for wire insulation, become of significance because they offer extra resistance to PD. The life time characteristics of nanocomposite materials enameled wires were investigated and confirmed previously [45,46].

It should be clear that PD diagnostics and related techniques are only some of the means to somehow approach the state of the insulating systems in a wind turbine generator. Other diagnostic techniques, going beyond the scope of this paper, can also be used and render themselves extremely useful. For example, thermography can be used in order to detect winding problems. In other words, thermoimaging can indicate inhomogeneous temperature

deviations in the phase windings, which in turn may cause further instabilities [24].

4. Further research

Regarding PD and the power electronics arrangements in conjunction with generator insulation, more work has to be performed w.r.t. the mechanisms of PD under such circumstances. A more fundamental approach is needed before the entirety of workings of PD in relation to the various rise times and various types of voltages is uncovered. How the PD process is influenced by the steep rising voltages? How the PD process is influenced by the magnitude of such voltages? In [35], it was speculated whether a PD change of mechanism occurs under the aforementioned conditions. Since it is not only the voltage level or the PD magnitude that are crucial, one should investigate the energy of the resulting PD in conjunction with the various types of voltage waveforms.

As a further step, one must bear in mind that since power electronics arrangements together with the generator are a whole system with components which interact, this interaction should be taken into account. To know how good is an insulating system separately from the others may be interesting from a pure academic point of view, but in a real industrial environment all interactions must be taken into account. In this respect, the lifetimes of insulated wires plus the voltages produced by the power electronics arrangements plus the generator/motor insulation are determined by the lifetime of the weakest components of such a system. The approach, according to which, the peak voltages are more or less constant and that the PD inception voltage of the winding insulation has a deterministic value is highly questionable [47].

Having said all that, one should bear in mind that no single measurement method can consistently reveal the condition of an insulating system. Consequently, despite the fact that PD measurements can reveal many weaknesses in an insulating system, other measurement methods may be performed in order to assess the state of the insulation [48]. Moreover, PD trend analysis may give a warning as to the state of an insulation but not a detailed diagnosis of the winding insulation [49]. As was pointed out in [50], a combination of diagnostic measurements and data analysis of the machine together with a detailed study of failure statistics may give a satisfactory condition evaluation of the reliability of the machine under question.

5. Conclusions

Power electronics arrangements may cause problems to the insulation of machines, mainly because of their additional voltage stressing. PD diagnostic techniques are a useful tool for the detection and recording of events that may cause insulation failure. However, such techniques offer a good method of recording the aging (premature or advanced) of an insulation but not a means of predicting its expected lifetime.

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